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DICE-RD: An Implementation of Rate-Related Damages in the DICE model

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by

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- Preliminary Version -

Abstract. A growing body of literature from the natural and the social sciences indicates that the rate of temperature increase is another key driver of total climate damages, next to the absolute increase in temperature compared to the pre-industrial level. Nonetheless, the damage functions employed in integrated assessment models that aim at studying the economics of climate change are usually based on the absolute temperature increase alone. Hence, these models neglect additional damages that will occur if the rate of temperature increase exceeds a certain threshold that overstrains the adaptive capacities of ecological and social systems. In the present paper, we implement such rate-related damages in the well-known integrated assessment model DICE-2016R. Using the resulting model variant DICE-RD we show for several different scenarios that an insufficient climate policy that ignores rate-related damages can lead to substantial economic losses.

Keywords: integrated assessment, DICE model, climate policy, rate of temperature increase

JEL: O44, Q54, Q58

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1 Introduction

Studying the economics of climate change, economists often use so-called integrated assessment models (IAMs) that combine the framework of a neoclassical growth model with a climate module. The major subject of study is the economically optimal emission mitigation path, which accounts for mitigation costs on the one hand and climate damage costs on the other hand. The latter are represented by a damage function that describes the economic impacts of climate change. Typically, these damage functions are based only on the absolute temperature increase compared to the pre-industrial level, but not on the rate of temperature increase, i.e., the increase in temperature that occurs per decade.

However, as stressed several times in the IPCC's Fifth Assessment Report (see IPCC 2014), and as underlined by a growing body of literature from the natural and - to a smaller extend - from the social sciences, the rate of temperature increase is also an important driver of overall damages caused by climate change. Consequently, neglecting such rate-related damages leads to suboptimal emission mitigation caused by an underestimation of damages.

This paper incorporates rate-related damages into the well-known DICE-2016R model by William Nordhaus (2018). Using the resulting model variant DICE-RD we analyze the potential welfare effects caused by the rate of temperature increase for several different scenarios. Each scenario compares the net output stemming from the optimal climate policy with the net output resulting from the reference policy that ignores rate-related damages. The differences in net output then can be interpreted as the economic losses that occur if rate-related damages are disregarded.

Employing DICE-2016R for our analysis has several reasons. Since the development of the first version (Nordhaus 1994), DICE has probably become the most popular integrated assessment model in the economics of climate change and its codes are publicly available.[1] Moreover, due to its popularity, DICE entails the advantage that our results are comparable with those of many other studies using the same model family.

The present paper proceeds as follows: Section 2 illustrates the importance of rate-related damages by some examples from the literature, and section 3 provides an overview on the incorporation of those damages in IAMs so far. In section 4, we shortly outline those parts of the DICE-2016R model that are important for our analysis, and in section 5, we incorporate rate-related damages into this model. In section 6, we discuss the results of our base scenario, and in section 7, we present a sensitivity analysis. Finally, in section 8, we summarize our main findings and highlight the need for further research.

[1] The source code of DICE-2016R can be downloaded at http://www.econ.yale.edu/~nordhaus/homepage/homepage/DICE2016R-091916ap.gms. Last access at 28/01/2019.

2 Impacts of the Rate of Temperature Increase

The harmful impacts caused by a high rate of temperature increase are best understood in the field of ecosystems and biodiversity (for an overview of studies see Warren 2006). Several species of flora and fauna are endangered by displacement or even complete extinction when the temperature increases faster than they are able to adapt to climate change. This adaptation may be a migration to new habitats with more suitable conditions,[2] or a change in the distribution of phenotypes within a given species towards the better-adapted ones (e.g., Visser 2008, Corlett and Westcott 2013). The capability of species to adapt by migration or genetic evolution, however, naturally depends on how fast the climate is changing. Hence, rates of temperature increase that exceed a certain threshold will reduce biodiversity by selecting for highly mobile or opportunistic species (Malcolm et al. 2002).

In particular, according to Leemans and Eickhout (2004), the adaptive capacity of forest ecosystems is much lower than the one of other ecosystems.[3] This is of considerable importance for the future trend of climate change, since the decomposition processes associated with a large-scale dieback of forests would lead to huge releases of CO_2 from the terrestrial biosphere thereby producing a significant feedback mechanism that accelerates global warming (Neilson 1993).

Acceptable thresholds for the rate of temperature increase, where the adaptive capacity of most species and ecosystems can cope with climate change, have been studied for more than 25 years. Early estimates suggest a "tolerable window" of not more than 0.1°C per decade (Vellinga and Swart 1991). More recent studies come to similar conclusions ranging from 0.05°C per decade (van Vliet and Leemans 2006) to 0.2°C per decade (Petschel-Held et al. 1999, Leemans and Eickhout 2004). In contrast, assuming "business as usual"-conditions Nordhaus (2018) calculates a temperature trajectory that implies an average rate of temperature increase of more than 0.3°C per decade during this century.

Besides ecosystems and biodiversity, the rate of temperature increase has impacts on several other sectors. The most obvious ones are agriculture and forestry. In agriculture, this relates to the adaptation of agricultural practices to changing environmental conditions. Additional costs occur whenever agents fail to adapt properly. However, proper adaptation requires the building of appropriate institutions that can create adaptive capacity in the agricultural sector (Lobell et al.

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[2] I.e., moving pole-wards or moving to higher altitudes in case of increasing temperatures (e.g., Loarie et al. 2009). However, as Malcolm et al. (2002) point out, the current rates of temperature increase require migration rates of species and biomes that are much faster than those observed during the complete postglacial period.

[3] For example, at a rate of temperature increase of 0.3°C per decade, 30% of all impacted ecosystems are still able to adapt within a century, but only 17% of all impacted forests (Leemans and Eickhout, 2004, p. 226).

2008). The faster climate change occurs, the less likely it is that these institutions can be established in time (Bellon et al. 2011, Tambo and Aboulaye 2012, 2013).[4]

In forestry, the impacts of the rate of temperature increase stem from commercially used tree species. These are affected by climate change because suitable regions are moving pole-wards due to global warming. When the rate of temperature increase is too fast, the species' population will overall decline because natural migration to suitable regions cannot cope with the pace of climate change. Consequently, in forestry proper migration to new habitats needs to be commercially assisted (Zhu et al. 2012, Pedlar et al. 2012).

Moreover, although specific literature on this topic is still scarce, several other sectors are potentially affected by the rate of temperature increase. In particular, the adaptation of human systems to climate change often presupposes huge time-consuming investments in knowledge, institutions and physical infrastructure. Prominent examples are adaptation requirements in the fields of coastal protection, freshwater supply and public health (see IPCC 2014, Chapter 16). A high rate of temperature increase entails the danger that these measures cannot keep up with the speed of warming.[5]

Another issue within the present context are so-called "tipping points" where climatic conditions change abruptly, irreversibly and in a manner hard to predict.[6] Lenton (2011) attributes the risks of passing such tipping points directly to the rates of temperature increase. However, the rates that would considerably increase the probability of passing such an event are far above those leading to the problems discussed above. Therefore, the issue of tipping points will be neglected in the following analysis.

3 Rate-Related Damages in Integrated Assessment Models

The damage function of DICE-2016R, as well as those of most other IAMs, relies exclusively on the absolute level of temperature increase. However, as substantiated in the last section, the rate of temperature increase is an important driver of damages as well. When the first generation of IAMs came up in the early 1990s, this issue had been discussed but, with the exceptions described below, the damage functions employed in IAMs do not account for rate-related damages.

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[4] Since adaptive capacity in the developed countries is considered to be high, the problems described above are primarily virulent in developing countries and in the subsistence farming sector.

[5] According to the IPCC (Field et al. 2014, p. 80), this problem is particularly pressing in the Polar Regions where the rate of temperature increase is about twice as high as the global average (see also Norwegian Polar Institute 2014).

[6] Examples are the shutoff of the Atlantic deep-water formation or the collapse of the Indian summer monsoon (e.g., Lenton et al. 2008).

The earliest exception traces back to the work of Peck and Teisberg (1994). The authors compare the results of their original CETA model, where damages are driven by the absolute level of temperature, with those of a modified version where damages depend on the rate of temperature increase. Their main finding is that optimal mitigation rates rather hinge on the shape of the damage function (e.g., quadratic or cubic) than on the question whether the absolute level or the rate of temperature increase is considered. The modified damage function used by Peck and Teisberg (1994), however, does not account for both variables at the same time. Consequently, the authors do not analyze the joint-effects of both damage categories. Moreover, nowadays the CETA model stemming from the early nineties is outdated in its parameterization.

Another IAM that partially accounts for rate-related damages is the FUND model (Tol 1997, Tol and Anthoff 2010). In their approach, however, only the impacts on agriculture depend on the absolute level as well as on the rate of temperature increase, whereas the impacts on all other sectors are modeled in the conventional way. Moreover, FUND exhibits only a limited degree of endogeneity since production activities and the resulting emissions follow exogenous trajectories. Consequently, in contrast to DICE, it is not possible to derive a complete first-best solution including the optimal level of production.

Also the PAGE model (Hope 2006, 2013) accounts to some extend for rate-related damages. This model, however, is a probabilistic simulation model that mainly serves to analyze the impacts of uncertainty. The degree of endogeneity is even lower than in FUND, because not only production but also mitigation rates are exogenous. Hence, within PAGE it is not possible to investigate the impact of rate-related damages on optimal climate policies.[7]

The most recent contribution is the work of Goes et al. (2011) who analyze the effects of aerosol geoengineering within the DICE-2007 model. Since the injection of aerosols into the atmosphere can lead to very fast changes in temperature, the authors use a modified damage function based on the rate of temperature increase in terms of 5-year and 30-year running averages. However, the focus of Goes et al. (2011) is solely on the effects of geoengineering. Their general approach as well as their damage function are not designed to investigate the role of rate-related damages in determining optimal climate policies.

Finally, it should be noted that all models mentioned above ignore that rate-related damages are only likely to occur if the rate of temperature increase exceeds a certain threshold. Neglecting this threshold-dependency in the calculation of optimal emission mitigation generates skewed results.

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[7] For a more throughout comparison between DICE, FUND and PAGE see Stanton et al. (2009).

4 The DICE-2016R Model

In the following, we describe only those parts of the DICE-2016R model that are important for our analysis.[8] Utility is expressed by a standard constant-relative-risk-aversion utility function:

$$U[c(t),L(t)] = L(t)\left[\frac{c(t)^{1-\alpha}}{1-\alpha}\right]. \tag{1}$$

The time index t indicates the specific period, c(t) is per capita consumption, L(t) is the population and α is the elasticity of marginal utility of consumption. The objective function to be maximized is the welfare function W. The latter consists of the discounted utility summed up over a finite time horizon of 100 periods each covering five years:

$$W[c(t),L(t)] = \sum_{t=1}^{T} \frac{1}{(1+\rho)^{t-1}} U[c(t),L(t)]. \tag{2}$$

The parameter ρ indicates the pure rate of social time preference, which is set at 1.5%. The production function is of Cobb-Douglas type $Y(t)=A(t)K(t)^{\gamma}L(t)^{1-\gamma}$ with Y(t) indicating gross output. A(t) is the total factor productivity, K(t) is the capital stock, L(t) is not only the population but also the labor input and γ is the elasticity of output with respect to capital.

The link to the climate module is formed via greenhouse gas emissions, which are caused by production due to an exogenous emission coefficient that declines over time. These emissions lead to a higher atmospheric greenhouse gas concentration that causes an increase in radiative forcing. In the next step, the increased radiative forcing triggers a higher level of temperature. The economic impact of this temperature increase is given by the damage function D(t), which describes the share of output lost due to climate damages:

$$D(t)=\psi_1 \cdot T_{AT}(t)+\psi_2 \cdot T_{AT}(t)^2. \tag{3}$$

$T_{AT}(t)$ indicates the increase of the global atmospheric mean temperature compared to the pre-industrial level, and ψ_i (i=1,2) are parameters that govern the shape of the damage function.

In order to avoid damages, emissions can be reduced by mitigation activities. The accompanying cost function $\Lambda(t)$ is defined in terms of the share of output spent for mitigation activities:

$$\Lambda(t)=\theta_1 \cdot \mu(t)^{\theta_2} \tag{4}$$

with $\mu(t)$ indicating the mitigation rate (i.e., the share of emissions avoided), and the parameters θ_i (i=1,2) determine the shape of the mitigation cost function.

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[8] For some more details on DICE-2016R see Nordhaus (2018). Since most parts of DICE-2016R are identical to DICE-2013R, the reader could also refer to the more throughout description of the latter model provided by Nordhaus and Sztorc (2013).

Finally, subtracting damages and mitigation costs from the gross output Y(t) yields the remaining net output $Y_{net}(t)=[1-D(t)-\Lambda(t)]Y(t)$ to be divided into consumption and investment. The latter equation highlights the typical trade-off in climate policies: More emission mitigation leads to higher mitigation costs Λ(t) resulting in a decreasing net output. However, at the same time, more emission mitigation leads to lower damages D(t) resulting in an increasing net output.

5 From DICE-2016R to DICE-RD

To transform DICE-2016R into DICE-RD we have to modify the damage function (3). The new function should incorporate the absolute level as well as the rate of temperature increase as a driver of damages. Moreover, it should account for the threshold-dependency of rate-related damages. Both requirements can be satisfied via replacing the original damage function D(t) by the new damage function Z(t):

$$Z(t):=[\psi_1 \cdot T_{AT}(t)+\psi_2 \cdot T_{AT}(t)^2]\cdot\delta(t)\,. \tag{5}$$

The term in square brackets on the RHS of (5) represents the original damage function D(t) and the multiplier $\delta(t)\geq 1$ accounts for the effect of rate-related damages.[9] The latter depend on the rate of temperature increase defined as $\Delta T_{AT}(t):=T_{AT}(t)-T_{AT}(t-1)$:

$$\delta(t):=1+B(t)\cdot\frac{\lambda}{100}\cdot\left[\frac{\Delta T_{AT}(t)-0.5\nu}{0.5\nu}\right]^{\omega}. \tag{6}$$

The parameters λ and ω govern the shape of the multiplier-function $\delta(t)$, and ν indicates the critical threshold for the rate of temperature increase measured in °C per decade. Since each period of DICE-2016R covers only five years, we have to use an internal threshold of 0.5ν in our model. The damage parameter λ is calibrated in such a way that it indicates the percentage increase in total damages if the increase in temperature between two periods is twice as high as the internal threshold, i.e. $\Delta T_{AT}(t)=\nu$. Moreover, according to the binary variable B(t) defined below in (7), rate-related damages only occur if the rate of temperature increase between two periods exceeds the internal threshold of 0.5ν. Otherwise, we obtain a multiplier of $\delta(t)=1$ and the new damage function Z(t) equals the original one D(t):

$$B(t):=\begin{cases}0 & \text{if} \quad \Delta T_{AT}(t)\leq 0.5\nu \\ 1 & \text{if} \quad \Delta T_{AT}(t)>0.5\nu\end{cases}. \tag{7}$$

[9] Systems that are already disturbed by the absolute level of temperature increase will probably have more problems coping with the additional stress stemming from a high rate of temperature increase. Therefore, we assume a multiplicative instead of an additive relationship between damages caused by the rate of temperature increase and damages caused by the absolute level of temperature increase.

As an example, Figure 1 illustrates the shape of the damage-multiplier $\delta(t)$ for the case of $\nu=0.1$, $\omega=2$ and varying magnitudes of the parameter λ.

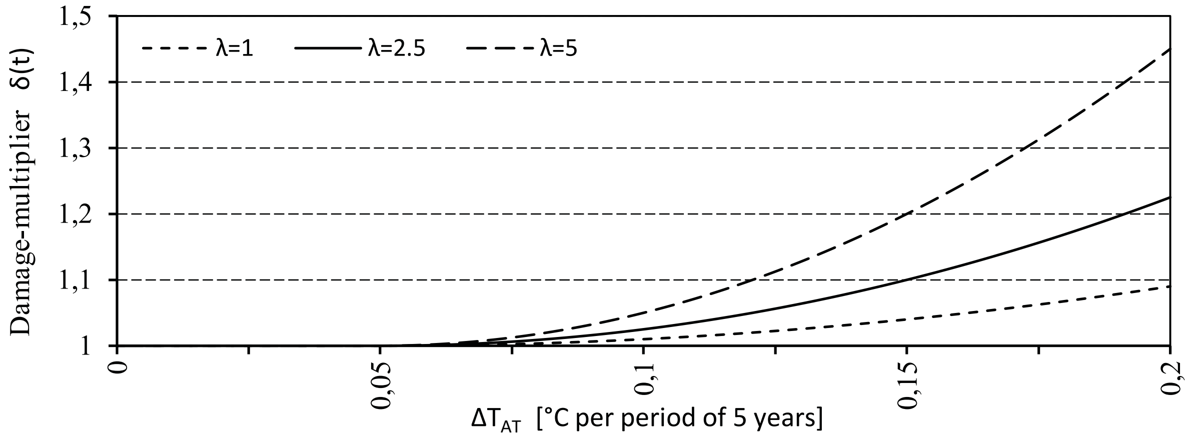

Figure 1. Shape of the damage-multiplier $\delta(t)$ for an example with $\nu=0.1$, $\omega=2$ and varying magnitudes of the parameter λ.

In our base scenario in section 6, we employ the best guess threshold of 0.1°C per decade, i.e. $\nu=0.1$. In contrast to this more or less reliable figure (see section 2), the range of the parameters λ and ω is almost completely uncertain. At the present state of insights from the social and natural sciences, we can only conclude that λ should be strictly positive, and ω should be larger than one since rate-related damages are expected to increase more than proportionately when the rate of temperature increase becomes larger (e.g., Leemans and Eickhout 2004). Our base scenario assumes a quadratic shape of the multiplier-function, i.e. $\omega=2$. Moreover, to avoid overestimating rate-related damages, we assume in the base scenario that damages increase only by moderate 2.5% if the rate of temperature increase is twice as high as the critical threshold, i.e. $\lambda=2.5$. This magnitude does not seem unrealistically high since ecosystems and agriculture, which are two of the sectors most affected by the rate of temperature increase, account for about 15 to 20% of total damages caused by an increase in temperature of 2.5°C compared to pre-industrial levels (Nordhaus and Boyer, 2000, p.91). Moreover, the effects of varying the parameters λ and ω as well as varying the threshold ν will be analyzed by a sensitivity analysis in section 7.1.

6 Results for the Base Scenario

In this section, we discuss the results stemming from our modified model DICE-RD and compare them to the results of the original DICE-2016R model.[10] As usual in studies based on DICE, we

[10] All calculations have been performed using the GAMS-software version win64/24.1 with the BONMIN solver. The latter is capable of solving mixed integer problems, which is necessary due to the use of a binary variable. The program files are available from the corresponding author on request.

consider only the results for the first 200 years although both models cover a time horizon of 500 years in total.[11] The major endogenous policy variable is the mitigation rate μ(t) that describes the share of emissions avoided. For convenience, in the text mitigation rates are expressed as percentages although in the original GAMS-files as well as in the figures below the variables μ(t) are expressed as decimals.

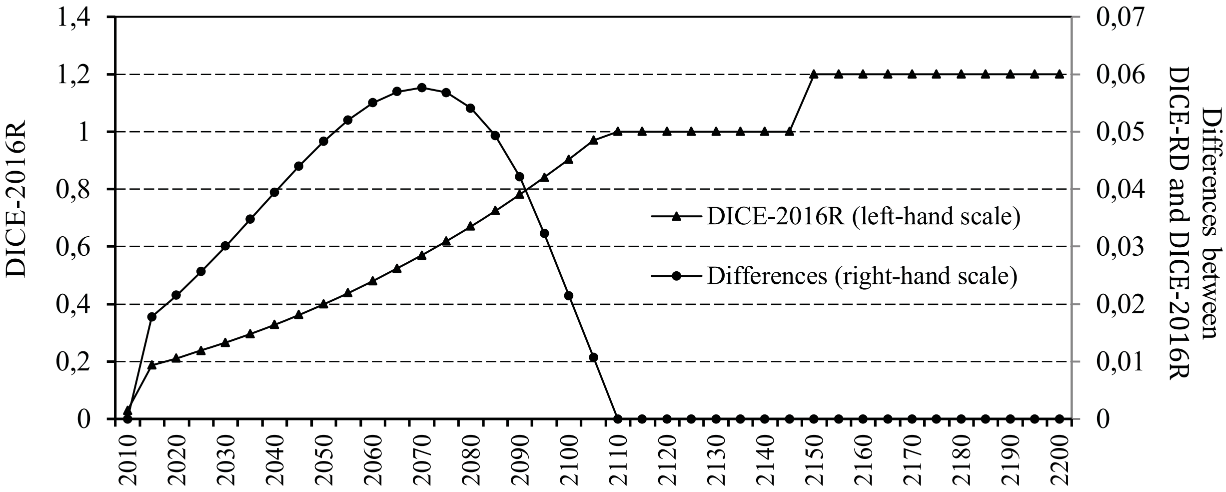

Figure 2. Optimal mitigation rates. Left-hand scale: DICE-2016R. Right-hand scale: Differences between DICE-RD and DICE2016R.

The left-hand scale of Figure 2 indicates the optimal mitigation rates resulting from the original DICE-2016R model as calculated by Nordhaus (2018). For the first period the mitigation rate is exogenously fixed. The first endogenously optimized mitigation rate occurs in 2015 with roughly 19%. From that point on, the mitigation rates rise steadily until they reach their temporary upper limit of 100% in 2110. Subsequently, in 2150 the mitigation rates jump to 120% since the upper limit is relaxed by the assumption that a "negative emissions"-technology becomes available.[12]

Moreover, it should be noted that the optimal mitigation path stemming from DICE2016R leads to a temperature trajectory that significantly violates the best-guess threshold of 0.1°C per decade during the first 100 years. Calculated over this time-span, the average damage-multiplier $\delta(t)$ amounts to a magnitude of approximately 1.09 under the assumptions of our base scenario.

The right-hand scale of Figure 2 indicates the results of our own calculations using DICE-RD with the base assumptions $\lambda=2.5$, $\omega=2$ and $\nu=0.1$. To enhance the graphical depiction, we do not display the *absolute* mitigation rates but their *differences* to the original mitigation rates

[11] Considering a longer time span would even reinforce our results since the vast majority of economic losses caused by neglecting rate-related damages occur not before the next centuries.

[12] E.g., technologies that use chemical reactions to capture CO_2 directly from the air (Socolow et al. 2011).

stemming from DICE2016R. As shown by Figure 2, these differences increase steadily until they converge back to zero in 2110. The reason for the latter behavior is straightforward since in 2110 the mitigation rates in both models reach their upper limit of 100% such that no more differences occur.

The preliminary results from our base scenario suggest that the impact of rate-related damages on optimal climate policies is non-negligible since the differences shown in Figure 2 rise up to a peak level of almost six percentage points around 2070. However, as already emphasized in section 1, the main objective of our analysis is to quantify the economic losses that are caused if climate policy ignores rate-related damages. The calculation of these losses is performed in three steps:

- In the first step, we calculate the net output that results if the optimal mitigation rates as derived from DICE-RD are employed.
- In the second step, we run DICE-RD with exogenous mitigation rates that are fixed to the levels stemming from DICE-2016R as shown at the left-hand scale of Figure 2. Hence, for roughly the first 100 years, we force DICE-RD to employ suboptimal low rates. This yields the net output that results if the applied mitigation rates neglect rate-related damages although they are present in the model.
- In the third step, the differences in net output between the optimal run (first step) and the run with fixed mitigation rates (second step) are calculated. These differences can be interpreted as the economic losses caused by a climate policy that neglects rate-related damages.

The results of this comparison in absolute (i.e., undiscounted) trillions of 2005 US-$ per year are shown in Figure 3.[13] Remarkably, the output losses for roughly the first 70 years are slightly negative. Negative losses imply that actually the suboptimal climate policy, which ignores rate-related damages, is economically beneficial in those periods. The reason is obvious since the optimal climate policy requires higher mitigation rates. This leads immediately to higher mitigation costs, whereas the majority of the benefits in terms of a lower increase in temperature accrue in the distant future. Consequently, when considering only the first couple of periods, employing suboptimal low mitigation rates leads to an increase in net output. Around the year 2080, however, this situation changes drastically: The output losses caused by ignoring rate-related damages become positive and increase sharply. The reason is that the optimal mitigation rates converge to the original rates stemming from DICE-2016R as shown in Figure 2. Hence, in the following decades, the additional mitigation costs implied by the optimal climate policy tend to zero, but the economy still profits from the increased mitigation rates in the past.

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[13] The same calculation can be performed for the variables consumption and investments. Apart from the absolute values, the resulting diagrams are mostly similar to those for net output.

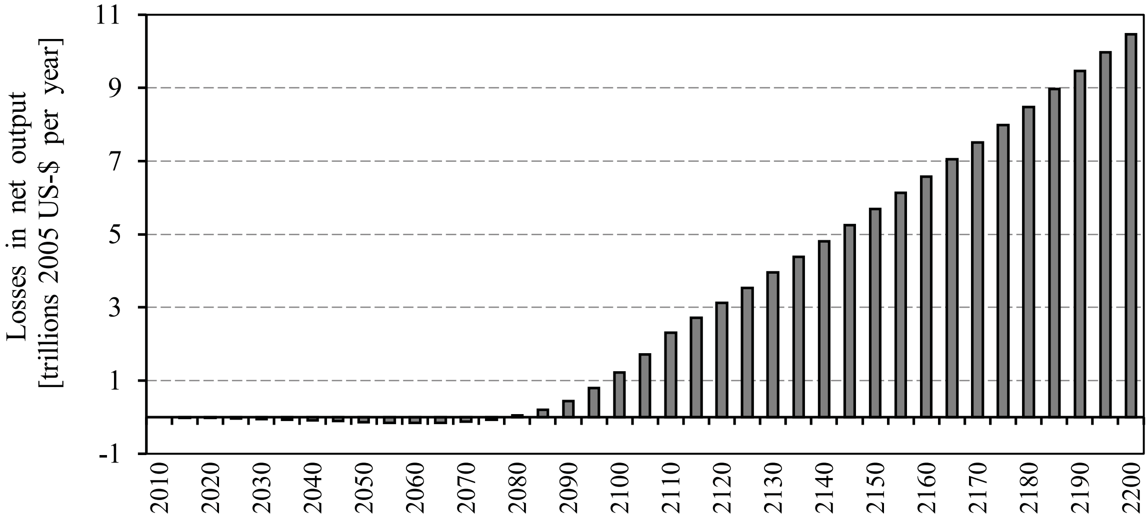

Figure 3. Losses in net output if climate policy ignores rate-related damages.

At first glance, the output losses depicted in Figure 3 seem to be enormous. It should be noted, however, that output is a global figure within DICE. Moreover, most of the output losses occur in the distant future. For the latter reason, we calculated the present value of cumulative losses in net output employing the real interest rates resulting from DICE-2016R.[14] The resulting magnitude amounts to 5.3 trillion 2005 US-$. Compared to the present value of net output in the optimum, this implies relative losses of only about 0.08%. Of course, due to the intertemporal distribution of losses, this figure might be biased by discounting (see also section 7.2).

7 Sensitivity Analysis

As a general shortcoming, the results of IAMs like DICE crucially depend on the magnitude of several parameters, which are highly uncertain or at least disputed in the literature (e.g. Pindyck 2013, NASEM 2017). Fixing the parameters of our multiplier-function (6) adds another source of uncertainty since the extent to which the rate of temperature increase affects ecological and social systems is poorly understood. Therefore, in section 7.1 we analyze the effects caused by varying the parameters of the multiplier-function.

Moreover, one of the most important parameters influencing optimal mitigation is the pure rate of social time preference, which is controversially discussed in the literature (e.g., Arrow et al. 1996, Hof et al. 2012). Concerning the issue under consideration, the effects of discounting might even be stronger since the output losses caused by neglecting rate-related damages mainly occur in the distant future. Consequently, the effects of varying the pure rate of social time preference are analyzed in section 7.2.

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[14] Note that these rates are declining in time. They range from 5.1% p.a. for the first period to 2.8% p.a. for the last period of the considered time horizon.

7.1 Parameters of the Multiplier-Function

As already emphasized in section 5, the parameter λ describes the percentage by which total damages increase if the rate of temperature increase is twice as high as the critical threshold. In our base scenario we assumed $\lambda=2.5$. Now we consider two additional cases: A "low damage"-scenario with $\lambda=1$ and a "high damage"-scenario with $\lambda=5$. As expected, an increase in λ reinforces the differences in mitigation rates whereas a decrease in λ causes the opposite effect (see Figure 4). However, even in the "low damage"-scenario we still obtain non-negligible differences that peak at about 2.5 percentage points around 2070.

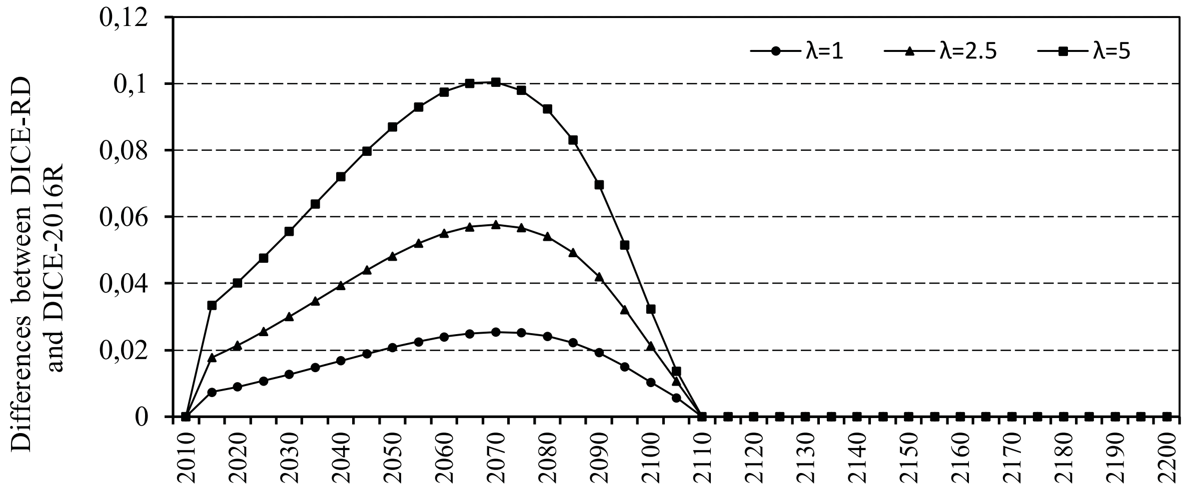

Figure 4. Optimal mitigation rates: Differences between DICE-RD and DICE-2016R for varying damage parameter λ (assuming $\omega=2$ and $\nu=0.1$).

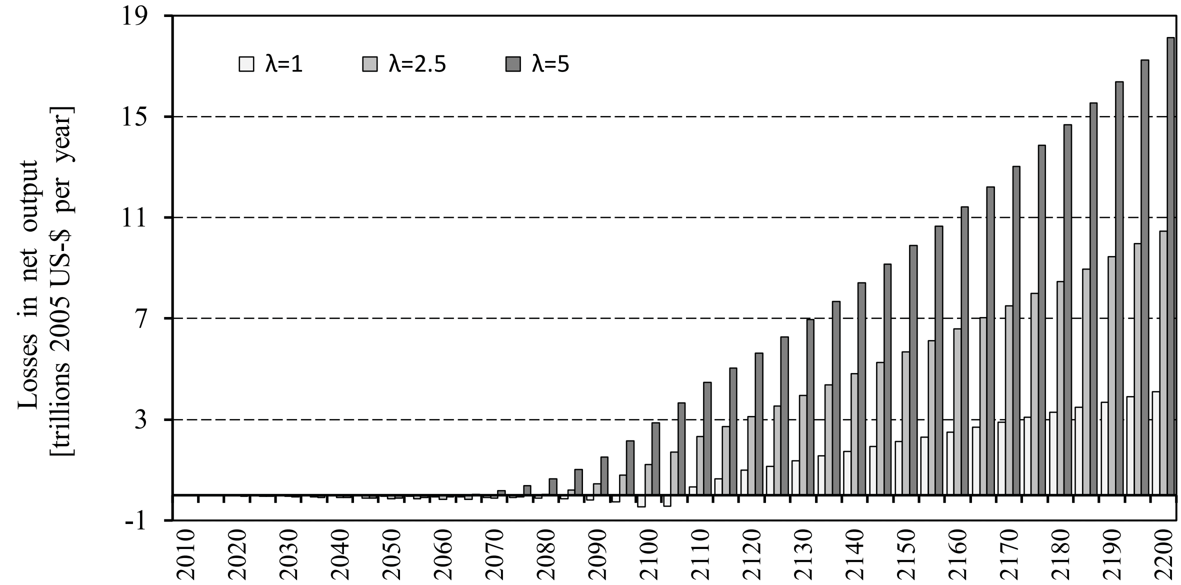

Figure 5. Losses in net output for varying damage parameter λ (assuming $\omega=2$ and $\nu=0.1$).

For all three scenarios, the losses in net output caused by ignoring rate-related damages follow the same general trend (see Figure 5): At the beginning of the time horizon they are slightly negative, but later on they become positive and start to increase more or less sharply. The only difference relates to their absolute levels. In the "high damage"-scenario the present value of losses in net output increases up to 11.2 trillion US-$ implying relative losses of about 0.17%. In the "low damage"-scenario losses shrink down to 2 trillion US-$ or about 0.03%, respectively.

Next, we turn to the effects of changing the parameter ω that determines the convexity of the multiplier-function $\delta(t)$. In addition to the quadratic case with $\omega=2$ considered above, we analyze a linear specification $\omega=1$ and a cubic specification $\omega=3$.[15] Compared to the quadratic specification, the linear one implies that rates of temperature increase below the calibration point of 0.1°C per period lead to higher damages, whereas rates above 0.1°C per period lead to lower damages. The opposite effects occur when switching from the quadratic to the cubic specification. The results of these calculations are shown in Figures A.1 and A.2 in the Appendix. Except for a short time span around 2090 to 2110, increasing or decreasing the parameter ω has essentially the same effects as increasing or decreasing λ (albeit the absolute magnitude of effects is somewhat different). Using the cubic instead of the quadratic specification increases the relative losses in present value of net output from 0.08% up to 0.22%, whereas using the linear specification we obtain a decline down to roughly 0.03%.

Finally, we analyze changes in the critical threshold for rate-related damages. Proceeding from the magnitude of 0.1°C/decade assumed so far, we consider a less severe threshold of 0.2°C/decade and a more severe one of 0.05°C/decade as suggested by the literature (see section 2). For both cases we again assume $\lambda=2.5$ and the quadratic specification $\omega=2$. Figures A.3 and A.4 in the Appendix show the results of these calculations. Assuming the less severe threshold of 0.2°C/decade, the impacts of rate-related damages vanish almost completely since the optimal solution of the original DICE-2016R violates this threshold only slightly during the first couple of periods. In contrast, for a threshold of 0.05°C/decade the differences in mitigation rates almost quadruple compared to the base scenario. Consequently, the losses in present value of net output increase up to 37 trillion US-$ implying relative losses of about 0.57%. These results show that the economic effects of rate-related damages react rather sensitively to changes in the critical threshold.

Figure 6 summarizes the results from our sensitivity analysis in terms of the relative losses in present value of net output caused by ignoring rate-related damages. Overall, these results suggests that potential economic impacts of rate-related damages range from almost negligible 0.03% to a more substantial 0.57%.

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[15] We are aware that the linear specification is a limiting case that is actually unrealistic in view of the present state of knowledge (see section 5).

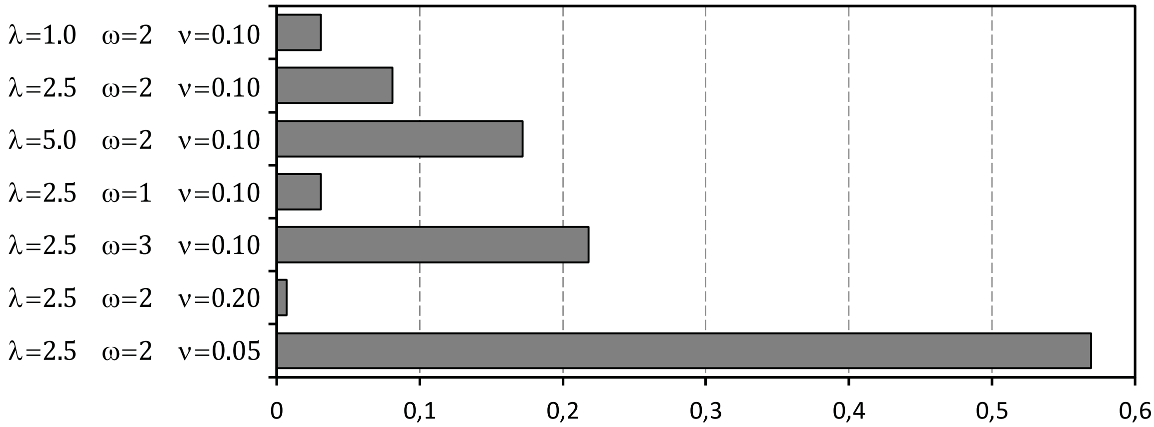

Figure 6. Summary of sensitivity analysis: Relative losses in present value of net output [%].

The variations considered in the sensitivity analysis above, however, can also occur simultaneously thereby reinforcing each other. Hence, to illustrate the possible extend of the problem at hand, we also calculated a "worst case"-scenario that combines the most critical assumptions. In detail, we assumed that the multiplier-function $\delta(t)$ is cubic, the threshold for the occurrence of rate related damages amounts to 0.05°C per decade, and total damages increase by 5% if the rate of temperature increase is twice as high as the critical threshold. As a result we found that differences in mitigation rates rise to a peak level of about 48 percentage points already around the year 2040, and the losses in present value of net output amount to 485 trillion US-$ or about 7.6%, respectively. Consequently, under "worst case"-conditions, which cannot be ruled out completely at the present state of knowledge, rate-related damages can lead to serious economic losses.

7.2 Pure Rate of Social Time Preference

In the following we again refer to the base scenario with $\lambda=2.5$, $\omega=2$ and a threshold of 0.1°C per decade, but now we consider the impacts caused by reducing the pure rate of social time preference ρ from 1.5% (as used so far) to 1% and 0.5%. Of course, in order to guarantee comparability, the lower values of ρ are employed in our extended model DICE-RD as well as in the original model DICE-2016R. In both models, decreasing ρ causes the mitigation rates to increase more rapidly since future climate damages gain more weight against early mitigation costs. In DICE-2016R, however, these effects are stronger than in DICE-RD. Consequently, lowering the rate of social time preference diminishes the differences in mitigation rates (see Figure 7). Moreover, the smaller is ρ the earlier the mitigation rates approach to their upper limit of 100% such that differences converge back to zero.

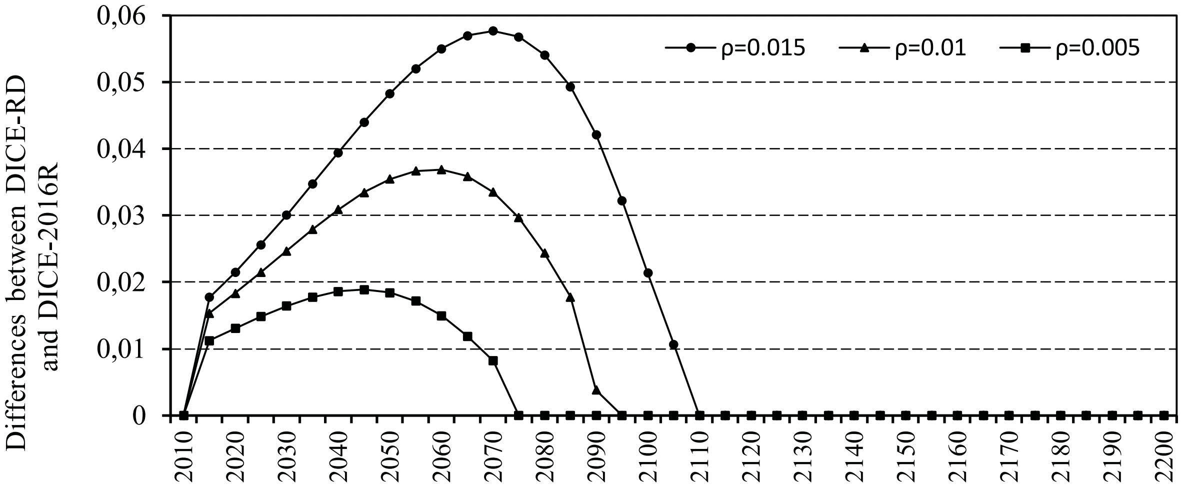

Figure 7. Optimal mitigation rates: Differences between DICE-RD and DICE-2016R for varying rate of social time preference ρ .

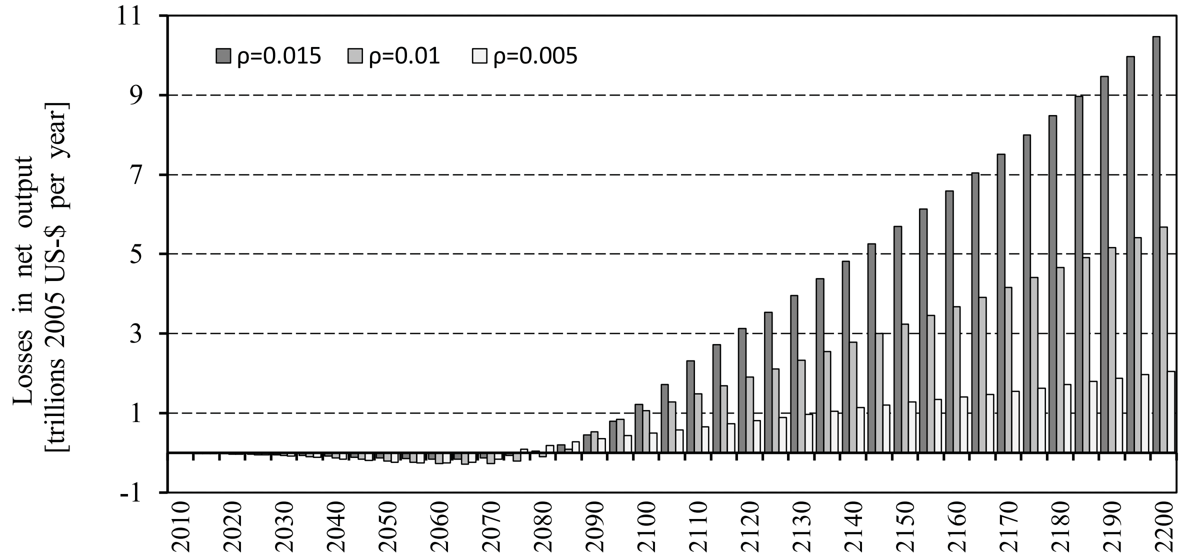

Figure 8. Losses in net output for varying rate of social time preference ρ .

Of course, the diminishing differences in mitigation rates also lead to smaller losses in net output. As shown by Figure 8, the corresponding decline amounts to roughly 50 to 80%. Calculating the present value of losses in net output, however, yields a result that is somewhat puzzling at first glance: Reducing ρ from 1.5% to 1% we obtain a slight increase from 5.3 to 5.5 trillion US-$, whereas a further reduction of ρ down to 0.5% induces a decrease to 4 trillion US-$. The answer to this puzzle is that lowering the rate of social time preference does not only increase mitigation rates but it has two additional effects: It increases total output via a higher degree of capital accumulation and at the same time it diminishes the real interest rates to be used for discounting.[16] Consequently, it seems to be more sensible to compare relative figures that are less distorted by these effects. Looking in this way at our calculations we obtain a clear-cut result: Reducing ρ always reduces the relative losses in present value of net output. For $\rho=0.01$ the relative losses drop down from 0.08 to 0.06%, and for $\rho=0.005$ they drop down further to almost negligible 0.025%. As these results show, applying a lower rate of social time preference in determining optimal climate policies could avoid a good deal of the problem under consideration.

8 Summary and Conclusions

Given the growing evidence concerning the importance of the rate of temperature increase, neglecting this aspect is an obvious shortcoming in the economics of climate change. Especially IAMs that aim at calculating optimal mitigation rates should incorporate all sources of damages in order to generate reliable results. In the present paper, we contributed to the corresponding literature in three ways:

- First, we showed how to incorporate damages caused by the rate of temperature increase into the well-known DICE-2016R model. In doing so, we particularly accounted for the hitherto neglected fact that rate-related damages are only likely to occur when the rate of temperature increase exceeds a certain threshold that overstrains the adaptive capacity of ecological and social systems. Moreover, we decided to model the relationship between damages caused by the absolute level of temperature increase and damages caused by the rate of temperature increase in a multiplicative instead of an additive manner. The reason is that systems, which are already disturbed by the absolute level of temperature increase, will probably have more problems coping with the additional stress stemming from a high rate of temperature increase.
- Second, using our modified model DICE-RD we analyzed various different scenarios in order to derive a large range of simulation results. A climate policy, which relies on the mitigation rates stemming from the original DICE-2016R model, can lead to significant rate-related damages since it implies a rate of temperature increase that heavily exceeds the best-guess threshold of 0.1°C/decade during the current century. Accounting for these potential damages, optimality requires a considerable increase in mitigation rates. Under "worst case"-assumptions, this required increase can rise to a peak level of about 48 percentage points.
- Third, we quantified the losses in net output caused by an insufficient climate policy that ignores rate-related damages. Depending on the scenario considered, the relative losses in the present value of net output compared to the optimal solution range from almost negligible

[16] With $\rho=0.01$ the real interest rates range from 4.8% p.a. for the first period to 2.3% p.a. for the last period of the considered time horizon. For $\rho=0.005$ the corresponding figures are 4.5 and 1.8%.

0.03% to a substantial magnitude of 7.6% in the "worst case"-scenario. Although the vast majority of output losses occur in the distant future, everything else equal the present value of relative losses is the higher, the higher the applied rate of social time preference is. Consequently, applying a lower rate of social time preference could avoid a good deal of rate-related damages.

However, the limitations of our work are obvious. Besides the well-known criticisms on IAMs in general (see, e.g., Ackerman et al. 2009, Pindyck 2013, 2017) it should be emphasized that our extension of DICE-2016R adds further uncertainties. Although it seems to be possible to narrow the empirical range of the critical threshold for the rate of temperate increase, there are no reliable data on the specific magnitude of rate-related damages available from the literature. Hence, we utilized scenario analysis to illustrate the potential effects of such damages. In order to increase the reliability of our results, it is necessary to narrow the empirical parameterization of our extended damage function. For this purpose, much more research is required in the natural as well as in the social sciences.

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Appendix

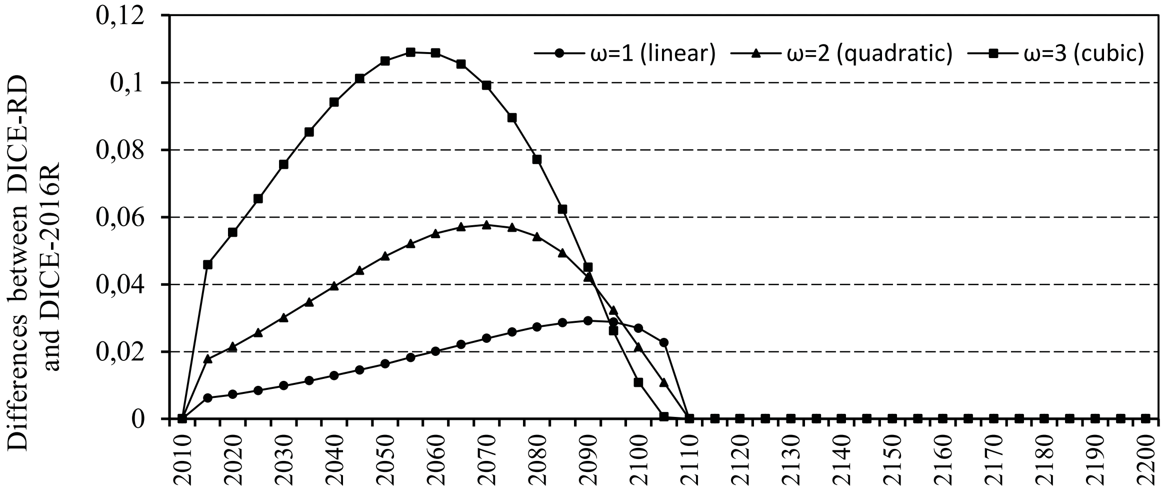

Figure A.1: Optimal mitigation rates - differences between DICE-RD and DICE-2016R for varying convexity parameter ω (assuming $\lambda=2.5$ and $\nu=0.1$).

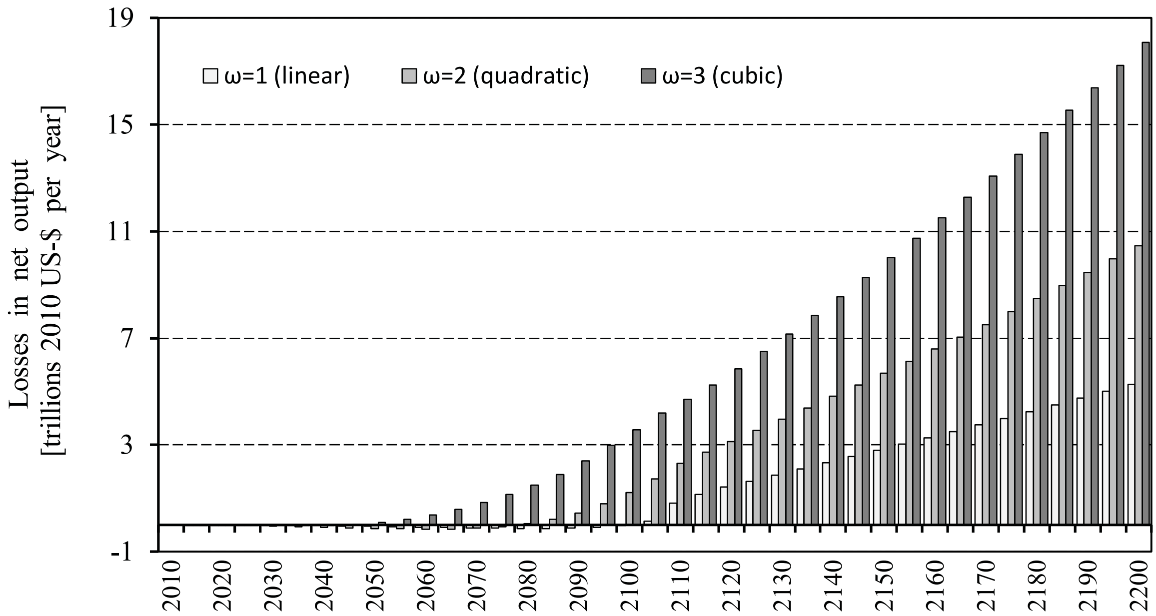

Figure A.2: Losses in net output if climate policy ignores rate-related damages for varying convexity parameter ω (assuming $\lambda=2.5$ and $\nu=0.1$).

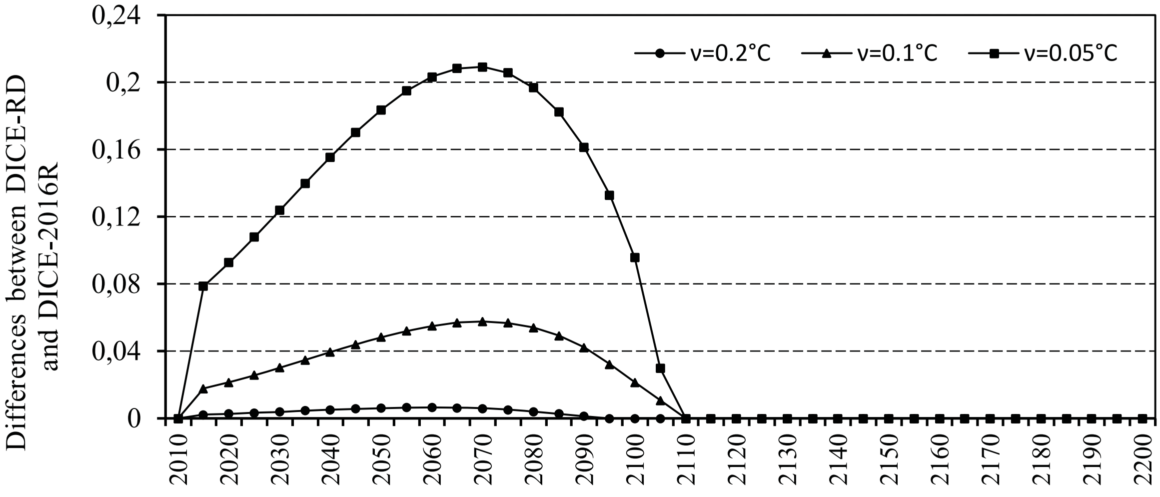

Figure A.3: Optimal mitigation rates - differences between DICE-RD and DICE-2016R for varying thresholds ν (assuming $\lambda=2.5$ and $\omega=2$).

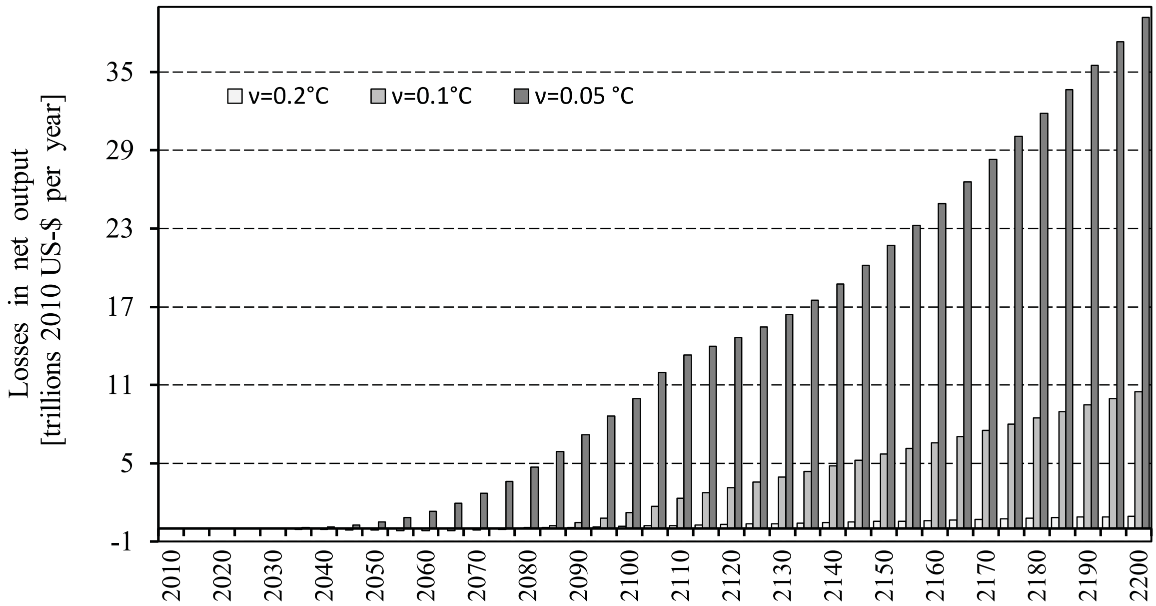

Figure A.4: Losses in net output if climate policy ignores rate-related damages for varying thresholds ν (assuming $\lambda=2.5$ and $\omega=2$).